SPACECRAFT CONTAMINATION

MODEL DEVELOPMENT

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ABSTRACT

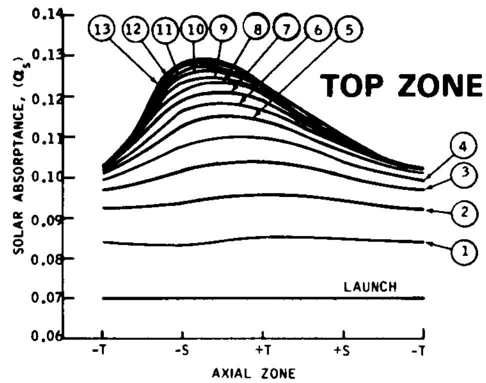
The development and use of a contamination mathematical computer model that has application to any on-orbit spacecraft system is defined. The model is modular, consisting of several major subroutines. These routines consider outgassing, venting and leakage, and thruster engines and point sources. The heart of the model, an integration program, has three major elements that are integrated into concise sets of equations. The basic elements are source kinetics, transport mechanisms, and reemission kinetics. Results of computer modeling activities and a related systems level contamination and analysis conducted by Aerojet ElectroSystems Company are presented. A correlation of the analysis with observed radiator degradation of a geosynchronous altitude satellite is presented to show the merit of the modeling approach.

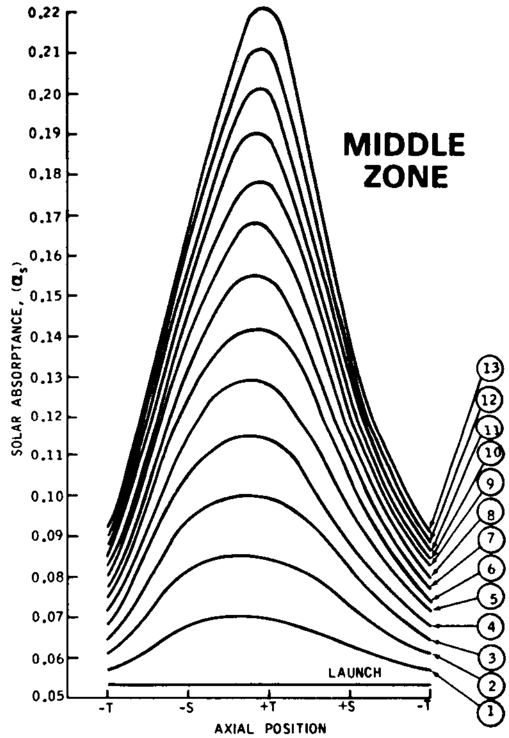
1.0 INTRODUCTION

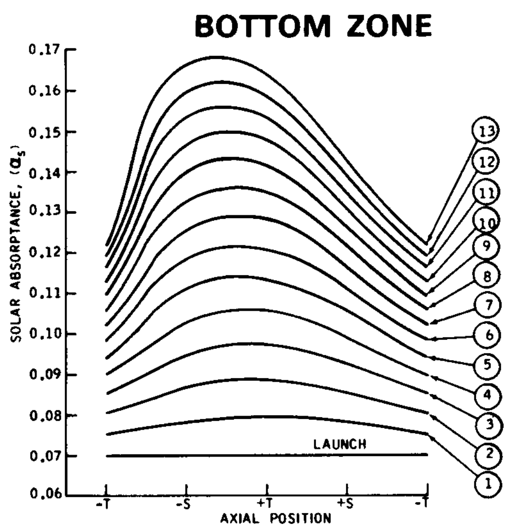
Radiators for passively cooled satellite systems require low values of solar absorptance (α_s) and high values of infrared emittance (ε_h). However, these thermal properties are subject to the effects of the space/satellite environment which can cause an increase in the α_s/ε_h ratio resulting in degradation of system thermal performance. This degradation may be caused by radiation damage to thermal control surfaces and/or contamination deposition of particulate or outgassed materials.

Analysis of the long-term temperature data of a geosynchronous satellite has shown a definite warning trend of the passively cooled systems. Thermal analyses performed with the tempature data indicated the solar absorptance of radiator surfaces was increasing with time. Solar absorptance "maps" of the absorptance trends were compiled for the radiators and are presented in Figure 1. However, a thorough understanding of causes and effects relating to this absorptance increase were subject to conjecture due to the limited information temperature data could provide. Therefore, means of providing additional required information for investigating the cause of the warming trends were initiated.

The warming trend highlighted the need for a contamination model that could identify the causes of the increase in temperature with time, and determine the effects of any design changes. Because of the many facets to such a mathematical model, the computer program to predict mass deposition (contamination) was structured so that it is assembled in modular fashion (Figure 2). The program is arranged in subroutines and concise algorithmic blocks within subroutines which control the many facets of data manipulation and solution techniques necessary to manage a complex model form efficiently. The modeling of spacecraft contamination involves many phases of manufacture and







MAP	DAYS FROM LAUNCH	YEARS FROM LAUNCH
	LAUNCH	LAUNCH
1	100	0.27
2	200	0.55
3	300	0.82
4	400	1.10
5	500	1.37
6	600	1.64
7	700	1.92
8	800	2.19
9	900	2.47
10	1000	2.74
11	1100	3.01
12	1200	3.28
13	1300	3.55

FIGURE 1. TRENDS OF SOLAR ABSORPTANCE AS A FUNCTION OF TIME ON-ORBIT FOR THE RADIATOR OF AN OPERATIONAL SATELLITE

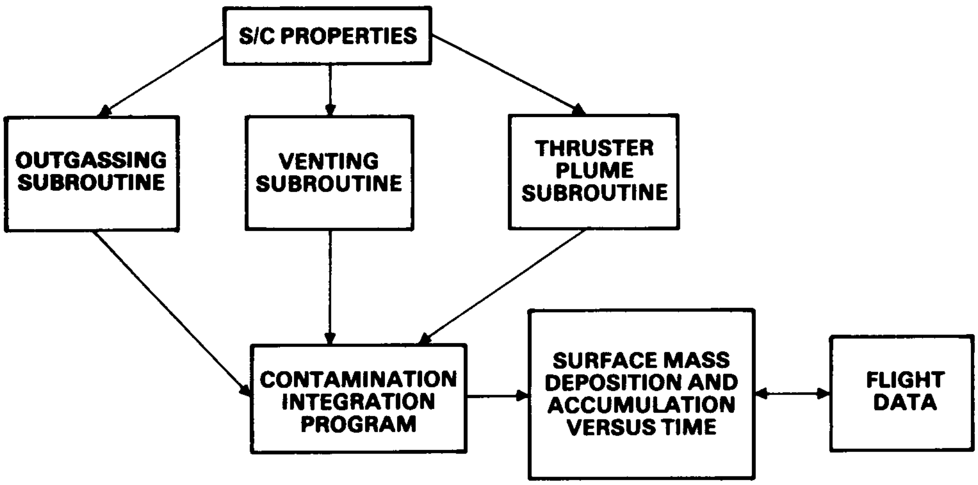


FIGURE 2. PROGRAM CONSTRUCTED IN MODULAR FASHION

ground handling, the launch environment, and orbital conditions. The modeling effort considered in this development deals only with the on-orbit environment (free molecular flow) experienced by the spacecraft. Results of related computer modeling activities at AESC are contained elsewhere in these proceedings.

2.0 DISCUSSION

The basic model is derived from the methods developed on the Satellite Contamination Program (SATCON).

In the SATCON Program, AESC is determining the effects of self-induced contamination of critical thermal control and optical surfaces. These data are being used to predict contamination effects on satellite system performance. The overall program is a multisystem study, with AESC concentrating on developing and verifying a general set of equations which describe contamination effects for optical and thermal-control systems. Satellite self-contamination in normal operation is the primary consideration. Briefly, the SATCON study is a progression of detailed tasks leading to the system overall effects evaluation as follows: (a) possible contamination source materials and target receptors are selected from candidate satellite surface materials; (b) for these materials, a theory of contamination mechanism and a set of equations are developed; (c) measurements of material emission kinetics are made under space conditions--a vacuum microbalance and a particle analyzer are used to determine particle composition and dynamics; (d) the transport mechanism is measured to validate the theory; (e) the thermal and optical effects of contamination are measured; and (f) testing is performed to verify the equations. The equations developed under this program provide the basic methodology for the mathematical model development.

The model presented in this paper is the composite of a data bank consisting of blocks of complex data formulated and formatted for efficient solution of the theoretical mathematical treatment developed under the SATCON program. An executive computer program was designed to effectively manage model data and solve for contaminant deposition rates by numerical solution of the governing theoretical differential equations.

Particular attention has been devoted to the development of a model with capacity applicable to large multinodal systems such as the external surface of entire spacecrafts and be within the realm of practical computer capability and use.

3.0 MODEL DEVELOPMENT

The Aerojet Mass Analyzer Program (AMAP) is designed to determine the contaminant source emission and reemission mass deposition rates on the surfaces of a vehicle in a space environment using line-of-sight theory and diffuse emission behavior. This program accounts for the deviation from these assumptions for surfaces such as thrusters with special shape factor input parameters.

The model presented in this paper is valid only for the free-molecular flow regime such as the vacuum space environment of an on-orbit satellite may provide. The development of the complete set of governing theoretical equations are presented by E. A. Zeiner in these proceedings.[1,2] The model presented in this paper is the result of general application technique and solution of this in-depth mathematical treatment as it applies to enclosure problems internal or external where space is the enclosing node.

While equally accurate for small nodal models, the model presented has been developed for practical solution capability of large multinodal enclosure problems of a general nature where free-molecular flow regimes are valid.

In-depth theoretical background and mathematical treatment development will not be presented in this paper as the comprehensive development is given elsewhere in these proceedings.[1,2] Equations programmed will be presented, however, without detailed description as that information is readily available.

The model presented assumes diffuse surface source emission and reemission, allowing for internodal distribution of contaminants incident to be described by geometric configuration factors (black body shape factors; F_{ij}) as are used in thermal radiation analysis. Capture coefficients (σ) are used to define the quantity of incident mass sticking and accommodated, thus being available for subsequent reemission consideration. Shape factors defining internodal distributions are a function of geometry and therefore apply to the system independent of temperature level or contaminant considered. Capture coefficients are a function of not only the contaminant type considered but also the temperatures of both the emitting and accommodating surfaces.

The initial distribution of mass emanating from vents and thrusters is defined by a set of shape factors which are defined as the mass rate initially incident on a surface divided by the total mass rate emanating from the vent or thruster (both are called vent nodes). This distribution is complex to determine and is a function of geometry, temperature, pressure, and contaminant. For some vent surfaces, the diffuse emission assumption may be adequate. For thrusters, plume analysis programs such as CONTAM II may be used. Defining these shape factors allows vent nodes to be handled in a convenient and similar fashion to other types of nodes and helps to prevent an unwieldy amount of input data.

The mass contamination model is concerned with VCM (volatile condensible materials) only. The governing set of differential equations appear in matrix form as follows for a one-contaminant, diffuse-source emission, and first-order diffuse re-emission:

$$\{\dot{md}\} = \begin{bmatrix} A \end{bmatrix} \{md\} - \dot{ms} \quad \{B\} \tag{1}$$

where:

$$\begin{bmatrix} A \end{bmatrix} = \begin{bmatrix} GF^{-1}S - \delta_{ij} \end{bmatrix} \begin{bmatrix} \diagdown & & \\ & k & \\ & & \diagdown \end{bmatrix} \tag{2}$$

where:

n	:	number of nodes in problem
$\begin{bmatrix} \diagdown k \diagdown \end{bmatrix}$	:	(n,n) diagonal matrix of nodal rate constants k_{ij} (sec^{-1})
$\{md\}$	:	(n) vector whose elements are the deposited mass surface density of each node (gm/cm^2)
$\begin{bmatrix} G \end{bmatrix}$	:	(n^2,n) matrix operator composed of F_{ij} functions.
$\begin{bmatrix} F \end{bmatrix}$	:	(n^2,n^2) matrix operator composed of algebraic functions of F_{ij} and σ_{ij}
$\begin{bmatrix} S \end{bmatrix}$	:	(n,n^2) matrix operator whose elements are functions of σ_{ij}
δ_{ij}	:	dirac (Kronecker) delta $\begin{matrix} i = j, \delta = 1 \\ i \neq j, \delta = 0 \end{matrix}$
$\{\dot{md}\}$	:	(n) vector whose elements are the net mass rate deposited (gm/cm^2-sec)

$\dot{m}s$: scalar mass loss rate from source which is a function of elapsed time in space (gm/cm^2-sec)

$\{B\}$: (n) vector whose elements are functions of F_{is} and σ_{si}; where "s" denotes source,

$$\left\{F_{is}\,\sigma_{si} \quad F_{2s}\,\sigma_{s2} \cdots F_{ns}\,\sigma_{sn}\right\}^T$$

Equation (1) represents a set of n first order non-homogenous linear differential equations which apply to a constant temperature profile throughout the nodal enclosure. The $\left[F\right]$ matrix becomes essentially a unity matrix when there are many nodes (F_{ij} values become small; << 1.0) and values for σ_{ij} are large (≈0.9, which is true in reality). With this assumption, inversion of the $\left[F\right]$ matrix is not necessary and it can be assumed to be unity. This simplification eliminates much computer core for solution routines and allows quick solution capability and computer capacity for large nodal models.

With these assumptions, the $\left[A\right]$ operator matrix reduces to the following form:

$$\left[A\right] = \left\{\begin{matrix} K_1(F_1, \sigma_1, -1) & K_2\ (\sigma_{21}F_{12}) & \cdots\ K_n(\sigma_{n1}F_{1n}) \\ K_1\ (\sigma_{12}\ F_{21}) & K_2\ (F_{22}\ \sigma_{22}\ -1) & \ldots K_n(\sigma_{n2}\ F_{2n}) \\ \vdots & \vdots & \\ K_1\ (\sigma_{1n}\ F_{n1}) & K_2\ (\sigma_{2n}\ F_{n2}) & \cdots\ K_n(F_{nn}\ \sigma_{nn}\ -1) \end{matrix}\right\}$$

Source emmission is defined by the Arrhenius expression:

$$m_s = -k_s\,M_o^{\;-k_s\,t} \qquad (3)$$

where:

M_o : mass surface density of VCM contaminant on a surface (gm/cm^2)

t : time elapsed in space (sec)

K_s : source contaminant rate constant (sec^{-1})

First-order reemission from a surface is defined as follows:

$$\dot{m}_e = -k_e \, m_d \tag{4}$$

where:

k_e : contaminant rate constant (sec^{-1})

Rate constants are functions of contaminant type and temperature of emitting surface while capture coefficients are functions of contaminant type and temperatures of both emitting and accommodating surfaces.

The program is capable of analyzing the contaminant mass distribution and subsequent degradation effects for problems with up to 130 nodes and 40 different source and deposited contaminants. Such a solution is found by computing a separate solution for each contaminant and superimposing these solutions for the complete solution. It is assumed that there is no chemical interaction or alteration of contaminants due to multiple contaminants on a surface. It is also assumed that the small quantity of mass (percentage-wise) which is elastically reflected and is not accommodated on any surface is lost to space.

With the assumptions made, equation (1) represents a set of differential equations which have applicability to any vacuum enclosure problem. As an example, the exterior of a spacecraft may be considered as an enclosure with space forming the enclosing node, having $\dot{m}_e$ values of zero. The model presented and programmed thus represents an accurate, concise, and efficient approach to the solution of vacuum contamination deposition problems with a generalized approach.

A topical flow diagram of the program is shown in Figure 3. The model computes mass deposition rates for multiple surfaces and multiple contaminants for a point in time. The solution is performed for a set of nodal temperatures and specified elapsed time in space (or vacuum). If a transient solution is desired, the program must be run for a successive number of cases, each being a stable amount of time between each other. In other words, a transient solution is found by running several successive cases and time stepping through the solution period; the elapsed time and nodal temperatures changing for each case. This time interval (stable time) is a period of time over which the deposition rates computed may be assumed constant. This time interval is a program input, and the program uses this time interval to compute the changes in source and deposited mass for each node for each contaminant present, thus preparing the nodal contaminant data for the next case to be run.

4.0 INPUT DATA REQUIREMENTS

The complete model consists of seven blocks of data. A tape of the basic model is read in (all or part of the seven blocks), then overriding cards may be read in to edit the tape model or add to it. This gives the program multiple case, multiple start capability. The blocks of input data are as follows:

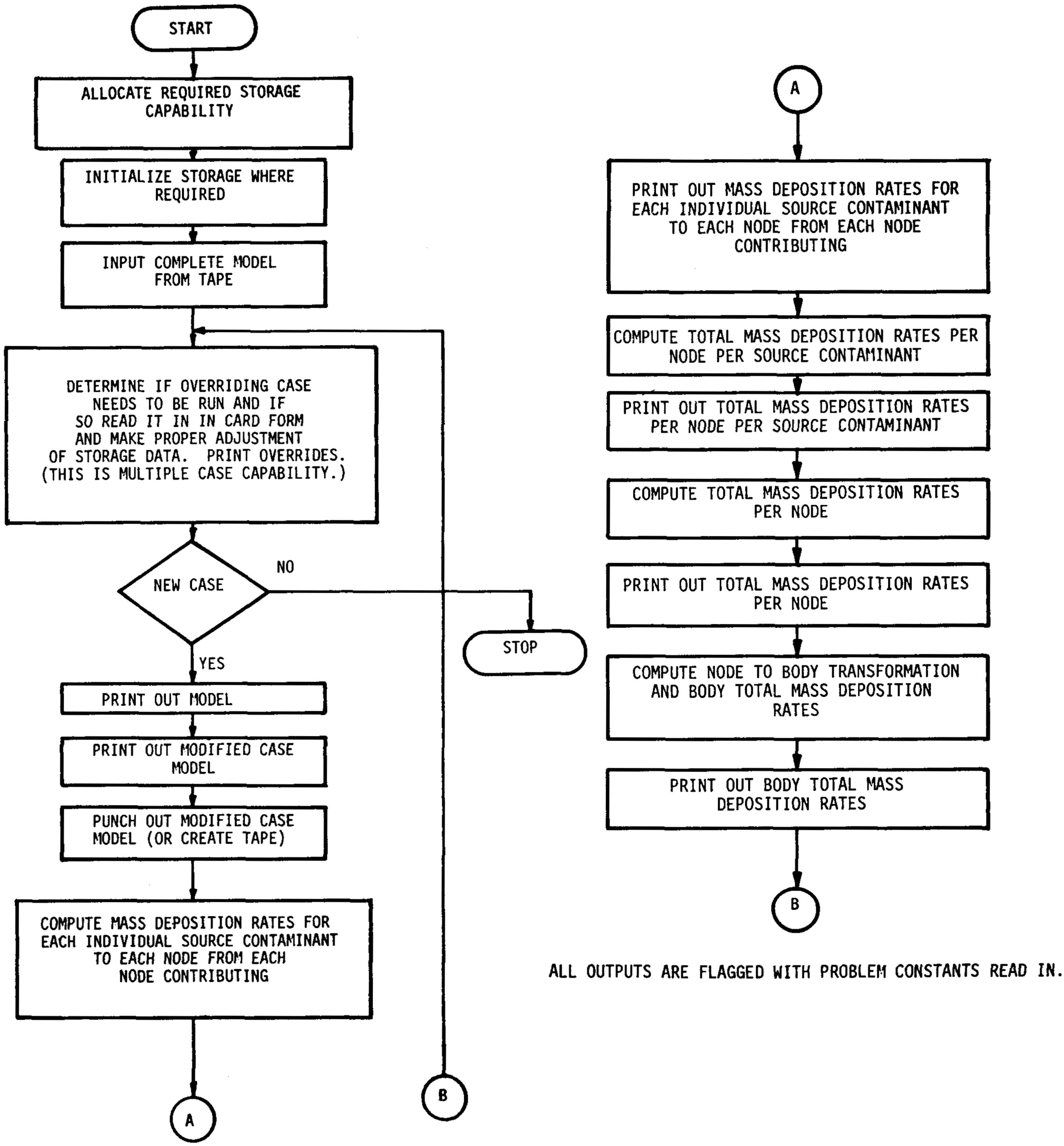


FIGURE 3. TYPICAL FLOW DIAGRAM OF PROGRAM

a. Problem constants - flag all program outputs, specify time after launch and increment of time over which rates computed are considered valid (stable time). Total capability of 15 constants.

b. Nodal data - node records contain flag indicating vent node or regular node, node number, node temperature, node area, and number of contaminants on the node. These are followed by a record for each contaminant present which lists: number of contaminant (ID #),mass surface density of source contaminant, and mass surface density of deposited contaminant. Program has capability of 130 nodes, 40 different contaminants.

c. Vent (point source) geometric shape factors - for each contaminant emanating from a thruster, a set of (non-black body) shape factors is included which defines contaminants' distribution to all surfaces it is incident on. Only nonzero values need be entered. Capability of 10,400 shape factors.

d. Black body shape factors - half of the internodal black body shape factor matrix is input (includes diagonal values) which defines the distribution of (nonvent) emitted contaminants (source and reemission) to surfaces they are incident upon. The rest of the matrix is solved for in the program by area reciprocity. Only nonzero values need be inputted. Capability of matrix for 130 nodes.

e. Tabulation of capture coefficients - table of capture coefficients (accommodation coefficients) as a function of temperature difference between emitting and receiving nodes must be inputted for each contaminant. Capability of 40 tables.

f. Tabulation of rate constants - table of rate constants as a function of temperature of emitting nodes must be inputted for each contaminant. Capability of 40 tables.

g. Node to body descriptions - block of data which lumps groups of nodes into bodies for determination of total mass source emission and deposition rates for bodies. Capability of 20 bodies each containing 20 nodes.

5.0 PROGRAM ROUTINES

The program is modular in nature being composed of several subroutines and algorithmic blocks within subroutines. Such a structure provides for improved program efficiency, reduced core usage and ease of editing for future improvements and modifications. The following subroutines are currently in service:

Main: Allocates required program storage, prints program header, controls program and terminates it.

Zero: Initializes storage where required.

Input: Reads in model tape and inputs model into storage.

Case: Reads in and prints out overriding cases (in card form) and adjusts model storage for case to be run. This routine gives the program multiple case (restart) capability.

Imprint: Prints out the basic tape model (if flagged) and prints and/or punches (if flagged) the models for individual cases run.

Stick: Linearly interpolates in tables of capture coefficients.

Rate: Linearly interpolates in tables of rate constants.

Comp: Sets up solution equations and solves them for all the various mass deposition rates and source emission rates for the printout options. All model inputs are required here for setting up the mass deposition rate differential equations. Changes in mass deposition for deposited and source contaminants over the time interval (stable time) are also computed here.

PCNDR: Prints out (if flagged) individual nodal exchange mass deposition rates between nodes for each contaminant.

PTCNDR: Prints out (if flagged) the total mass deposition rate and source emission rate for each node for each contaminant.

PTNDR: Prints out the total mass deposition rate and source emission rate for each node.

PTBDR: Prints out the total mass deposition rate and source emission rate for each body.

PBLK2: Computes a new block of nodal contaminant data based upon changes in mass rates computed in routine COMP over the stable time increment specified. It also prints and/or punches (if flagged) out this block of data for evaluation or use in another case.

6.0 PROGRAM OUTPUT

All outputs must be flagged by nonzero problem constants in order to be printed and/or punched. This prevents accidental output of unwanted data making user conscious of output. Output can be extensive and user must beware. Should errors be made and certain groups of constants not flagged, the program will terminate.

The following outputs and problems constants are available:

Constant	Control Feature
(1)	Print entire tape model.
(2)	Print entire model with individual case changes.
(3)	Punch out entire model with case changes.
(4)	Print mass deposition rates for each node from each node for each contaminant contributing.
(5)	Print total mass deposition rate and source emission rate for each node for each contaminant.
(6)	Print total mass deposition rate and source emission rate for each node.
(7)	Print total mass deposition rate and source emission rate for each body.
(8)	Time increment for interval over which rates assumed valid (stable time).

(9) Time after launch or start of source emission.

(10) Punch out new block of nodal data as a result of mass exchanges occurring over time increment (problem constant 8).

Constants 12 through 15 currently not used.

7.0 MODEL PREDICTION

A contamination assessment was performed for a synchronous altitude spacecraft to determine if the mass distribution would be similar to that of the solar absorptance degradation experienced on the radiators. This spacecraft was used to check out the contamination analysis program because of the large amount of thermal performance flight data available. The specific input parameters for this model consisted of: (a) 95 surface nodes, (b) 33 source materials, (c) normal operation hydrazine thruster profile, and (d) an 18-month prediction time. Two cases were considered when inputting data. The first case used the temperature data recorded at the end of 18 months on orbit. The second case used the initial stabilized on-orbit temperatures. The mass distribution and the major contributing sources were predicted for the 95-node model. These results were compared with the observed performance (α increase) after 18 months. This comparison was limited to two different radiator solar absorptance maps derived from temperature data in previous studies. Results of the analysis are shown in Figures 4 through 6.

Figure 4 shows the predicted contamination on the primary radiators for 18 months on orbit (18-month temperatures used). As can be seen, a preferential component of mass buildup exists near the center of the radiator. Figure 5 shows the preferential shape of the radiator degradation after 18 months on orbit. Normalizing the curves and superimposing Figures 4 and 5 yields Figure 6. It is clear

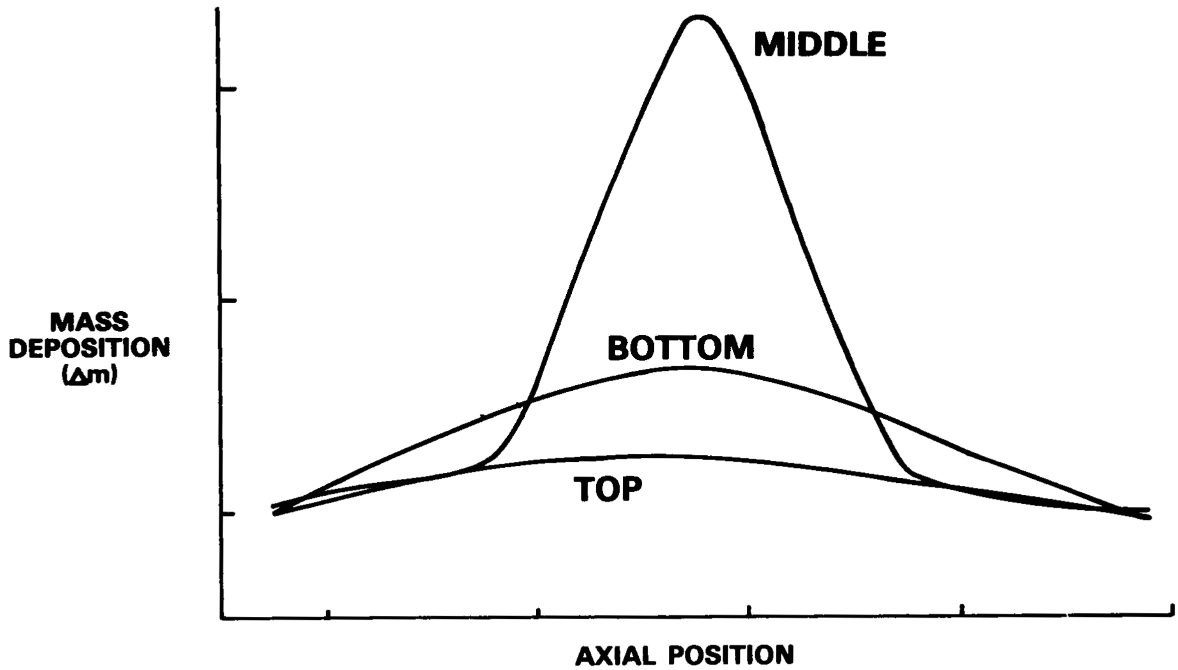


FIGURE 4. PREDICTED CONTAMINATION ON PRIMARY RADIATOR FOR 18 MONTHS IN ORBIT

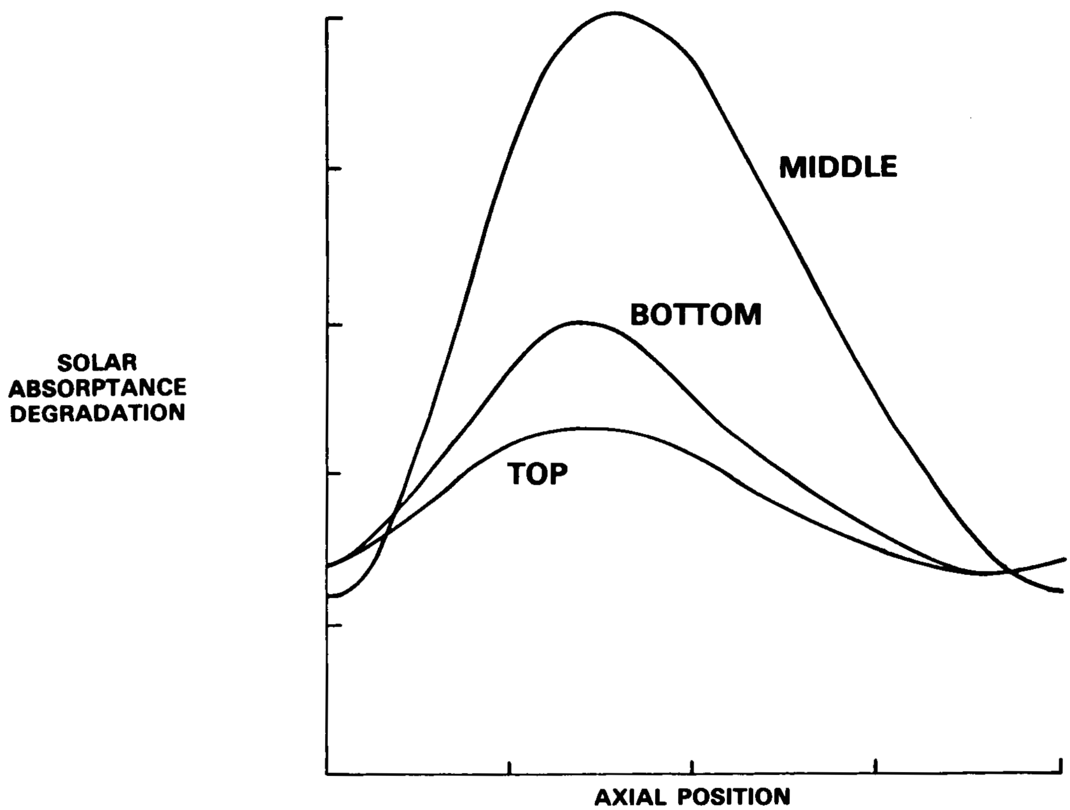


FIGURE 5. PRIMARY RADIATOR DEGRADATION AFTER 18 MONTHS (FLIGHT DATA)

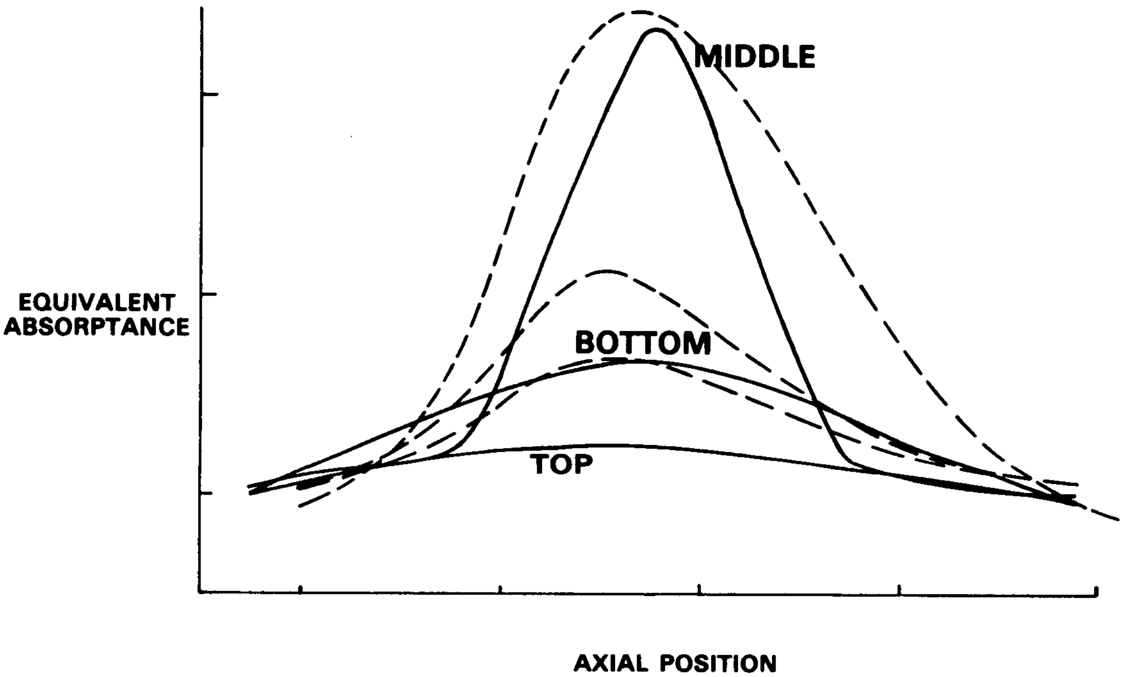


FIGURE 6. COMPARISON OF PREDICTED MASS DEPOSITION TO SOLAR ABSORPTANCE CHANGES

that the mass distribution on the primary radiator closely resembles the solar absorptance degradation distribution.

8.0 RESULTS AND CONCLUSIONS

The results show the major sources of contamination to be venting of the electronics enclosure and thruster plume effluents. A list of sources of contamination to the satellite radiators is presented in Table 1.

TABLE 1 SOURCES OF CONTAMINATION TO RADIATORS

Sources	Percentage
Electronics enclosure venting	68
Thruster plume effluents	28
Reaction wheel oil	1.0
Others	3.0

A second case that used the stabilized initial orbital temperatures was run. The results show the shape of the curves to be identical with those of the first case; however, there was a 10 to 12 percent increase in the mass deposited over the primary radiator when the initial orbital temperatures were used. These results suggest the model is a good representation of the mass transport mechanism and the model results are not strongly dependent upon the temperature distribution.

Continuing studies are being conducted at the time this paper is written which confirm the value and utility of the model and provide improved verification of the model as being representative of the mass transport mechanism. The model provides an efficient, comprehensive and concise generalized approach to solving the mass deposition contamination problem in a free-molecular flow environment.

To date there is insufficient experimental data available to positively correlate mass deposition with solar absorptance increase in a comprehensive fashion. However, with the mass deposition predictive technique developed, potential contamination problems on new spacecraft are being avoided or minimized in the design phase and improved detection and evaluation of optical and thermal problems on existing designs have become a reality.

ACKNOWLEDGMENTS

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